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CANDU Advanced Fuel TechnologyDevelopment in China– Perspective, Roadmap, and Status

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ABSTRACT –Because of high neutron economy, simple fuel bundle design, and on-power refueling, CANDU could use recycled uranium economically and efficiently and be the breakthrough of Th nuclear utilization. Based on the above technical advantages of CANDU and the closed nuclear fuel-cycle strategy in China, CANDU could play an important role in Chinese nuclear energy development. CANDU reactors could be constructed to match with PWRs, reprocessing plants and FRs to use the limited natural uranium more effectively in China and could be the R&D platform for thorium nuclear utilization and Th-U circulation. In order to realize this perspective,Third Qinshan Nuclear Power Company (TQNPC), cooperated with Candu Energy ltd. (CE), decided to develop CANDUadvanced fuel technology. Up to the present, NUE demonstration test has completed successfully, NUE full core implementation has got permission from the regulator, and Advanced Fuel CANDU Reactor (AFCR) with DRU or LEU/Thfuel has been conceptually designed. CANDU technology has received more and more recognition along with the development of CANDU advanced fuel technology in China, and we willdedicate to develop CANDU advanced fuel technology and AFCR continuously.

Introduction

In the "Mid-Long Term Development Plan for State's Nuclear Power of China (2005-2020)" issued in 2007, China put forth the specific requirements of "adhering to the technical line of closed nuclear fuel cycle" and "developing nuclear fuel industry with appropriate advance". However, at present, the closed nuclear fuel cycle industry is still in the starting phase in China. Reprocessing is an obvious restricting factor in the development of closed cycle industry. The development of reprocessing industry has been lagged behind the actual demand because on one hand, in the nuclear energy development in the initial period, China attached importance to the development of nuclear power technologies, but the development of closed nuclear fuel cycling technologies was neglected, and on the other hand, the economic performance of reprocessing is not so attractive.

To increase the economic performance of reprocessing industry, all products in reprocessing process must be utilized as far as possible.Among the reprocessing products, highly radioactive wastes account for about 5%, which should be disposed geologically; about 1% of plutonium can be recovered, to be used in fast reactors as an important strategic resource; however, no recycling for use has been considered for the recovered uranium, accounting for 94% of the reprocessing products.

Furthermore, in the current nuclear fuel cycle in China, only the uranium-plutonium cycle system has been taken into account. As China has rich thorium reserves, out research on utilization of nuclear energy of thorium resource and appropriate development of thorium-uranium fuel cycle technology can serve as supplement to the uranium-plutonium fuel cycle technology, which is conducive to ensuring the sustainable and healthy development of nuclear energy.

Because of the advantages of CANDU such as high neutron economy, simple fuel bundle design, and on-power refueling, CANDU is more advantageous over PWR in using recovered uranium or thorium resources. In general, using recovered uranium or Th in CANDU is technically feasible, and can produce obvious economic benefits. Based on the feasibility of using RU and Thfuel in CANDU and the closed fuel-cycle strategy, there are bright prospects lying ahead for CANDU in China.

1. Feasibility of utilizing RUorTh in CANDU

1.1. RU utilization

According to domestic and international research practice, CANDU is more advantageous over PWR in using recovered uranium, as detailed in Table 1. In general, using recovered uranium in PHWR is technically feasible, and can produce obvious economic benefits.

Table 1 Comparison of using recovered uranium with CANDU and PWR

	CANDU	**PWR**
Re-enrichment	Not required	Required
Radioactivity level	2~3 times	About 80 times
Fuel fabrication, transport and use	Minor change	Major change
U-235 to compensate extra neutron depletion of U-234 and U-236	Very low	About 0.3-0.5%
Fuel economic performance	Lower than the current fuel cost	3~4 times

If new CANDU reactors could be constructed to match with the repocessing plants development, all the RU from the reprocessing plants could be reused, which could save natural uranium resources and increase the economic performance of reprocessing plant. A 200t/y reprocessing plant could repocess the spent fuel from 8 PWRs, and the recycled U could supply 3 CANDU reactors.

1.2. Thorium utilization

Thorium is a potential resource of nuclear energy. Thorium(Th-232) is a fertile material. After absorbing a neutron from the driver isotope fission, the Th-232 can turn into the fissile isotope of u-233, and then u-233 fission to produce energy. CANDU reactor has better neutron economy, which means there will be enough neutrons for Th-232 to turn into fissile isotope. since the structure of CANDU fuel bundle is simple, and CANDU could be online refueled, the fuel management of CANDU is much simple then other reactor types. CANDU is considered as one of the best way to use thorium resources.

Several years ago, the National Energy Administration (NEA) of China organized an expert symposium in nuclear utlization of thorium resource. The symposium proposed that, giving the outstanding advantages of PHWR and fast reactor breeding zone in nuclear utilization of thorium resource, the state should make use of the feature of CANDU in flexible fuel management, and strive to make breakthrough in the application of thorium resource in CANDU in conjunction with the favorable conditions of international cooperation.

2. Perspective of CANDU in Chinese nuclear power development

Based on the feasibility of utilizing RU or Th, the ability of producing isotopes, and the closed nuclear fuel-cycle strategy in China, CANDU could play an important role in Chinese nuclear power development.

2.1. Proposal on nuclear power development strategy

In the near term, efforts should be made to complete a closed nuclear fuel small cycle system with a pilot plant as the center, by taking into account the conditions of reprocessing industry, the research and development of using recovered uranium in PHWR and development status quo of fast reactor in China, to get through the technical line. In the meantime, the research work on using thorium resource nuclear energy should be started.

In the medium term, a large closed nuclear fuel cycle system of commercial scale based on big reprocessing plant should be built. A big reprocessing plant of 200~800t/a and associated MOX fuel plant will be built, to supply fuel to demonstration fast reactor, and AFCR reactor matching with big reprocessing plant will be built, to realize the use of recovered uranium from the big reprocessing plant. According to a preliminary estimation, a 200t/a reprocessing plant can process spent fuel from 8 PWR's of 1000MW class, recovering plutonium about 2t, sufficient for 2 fast breeder reactors, and recovering uranium about 190t, for use by 3 PHWR reactors.

In the far term, technological development for closed fuel cycle of fast reactor breeding cycle will be completed, to realize industrialized development of fast reactor breeding system, and gradually realize the transition from thermal reactor closed cycle to fast reactor closed cycle. The thorium-uranium cycle technology has basically become mature, and can be used as an effective supplementary and backup means too uranium-thorium cycle. In the meantime, the isotope tritium in PHWR can be used as nuclear fuel in the research and development and testing of fusion reactors.

2.2. Position of PHWR

The above-mentioned development strategy for closed nuclear fuel cycle has taken into full account the development orientation of closed nuclear fuel cycle in China and the existing condition of coexistence of PWR, PHWR and fast reactors, and is therefore feasible. PHWR reactor, with its good neutron economic performance, high fuel flexibility and ability to produce isotope in large scale, will play an important role in the nuclear energy and nuclear technology industrial development in China in near and medium terms, and a summary has been made as shown in Table 2.

Table 2 Role of PHWR in the development of nuclear energy and nuclear technology industry

Period	Position of PHWR
Near term (-2020)	➢ Directly use recovered uranium, to raise the utilization rate of uranium resource and increase economic performance of reprocessing ➢ Carry out research on nuclear utilization of thorium resource as a test platform ➢ Produce cobalt isotope in large scale
Medium term (2020-2030)	➢ Further use recovered uranium ➢ Realize nuclear energy use of thorium resource, and open up new source of nuclear fuel

Period	Position of PHWR
	➢ Carry out research on thorium-uranium cycle, to reduce pressure in the development of fast breeder reactors ➢ Produce cobalt isotope in large scale
Far term (2030-)	➢ Generate power by using the recovered uranium accumulated in PWR operation ➢ Thorium-uranium cycle as the backup means of uranium-plutonium cycle ➢ Produce cobalt isotope in large scale ➢ Produce isotope tritium to provide nuclear fuel for the development of fusion reactors

3. CANDU advanced fuel technology development roadmap

The U-235 content in RU is about 0.8% ~ 1.4%, which is higher than NU, accordingly there are two options to recycle RU in PHWR. One is to blend RU with DU to make the fuel which is equivalent to NU, and the new fuel is named NUE. The other one is to use RU directly, and the effect may be the same as LEU. Direct use of RU will get higher profit, better safety, as well as more difficulty of design and license, and larger investment.

Considering Chinese industrial basis of PHWR, it is advisable to use NUE firstly, and the technological development and demonstration test are needed. The next step is to develop and construct a new CANDU reactor to implement derivative of RU fuel, which has higher enrichment of U-235 and could utilize RU more effectively and decrease spent fuel volume by about 30%. The above arrangements could be condensed into 3 steps, which are NUE demonstration test in CANDU-6, NUE full core implementation in CANDU-6 and DRU full Core implementation in new built AFCR.

Because AFCR with DRU fuel has higher burnup, which would be benefit for thorium turning into fissile nuclides, AFCR could be used as the platform for the research of thorium nuclear utilizationwhen AFCR with DRU fuel has been constructed. When enough experiences about rhorium nuclear utilization have been got, the construction of thorium fuel reactors could be strarted, or the AFCRs with DRU fuel could be transformed into AFCRs with thorium fuel.

The development roadmap is described as figure 1.

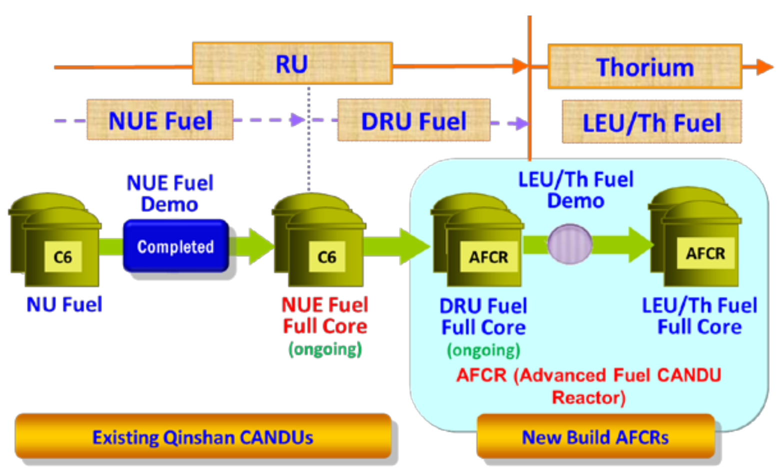

Figure 1 Development roadmap of CANDU advanced fuel technology

4. Development status

4.1. NUE implementation demonstration test

In Mar. 2010, after sufficient analysis and justification and obtaining approval by the National Nuclear Safety Administration (NNSA), natural uranium equivalent fuel was loaded in two channels of Unit 1, to start the in-core test following the management process flow of natural uranium fuel. The test was completed in Mar. 2011, and then under water inspection and hot cell inspection were performed for the natural uranium equivalent spent fuel.

The demonstration test of NUE fuel includes fuel design, manufacture, irradiation and in-bay inspection, and all the work finished successfully. NUE fuel could be produced by current NU fuel product line with a little modification, and the radioactivity of new NUE bundles are acceptable. The NUE fuel has the same physical characteristics, power-producing ability, and operation performance as NU fuel.

The in-core monitoring and in-bay inspection show that there are no difference between NUE Fuel and NU fuel, and there is no technical obstacle in NUE fuel full core implementation.

4.2. NUE full core implementation

When the NUE bundles were loaded into the core to start the demonstration test in 2010, TQNPC immediately started the development work for using natural uranium equivalent fuel in a whole CANDU reactor with the help of Canadian cooperators.

There are totally three main parts in NUE full core implementation project, i.e. physics design and safety analysis, RU purchase, and product-line modification. The physics design and safety ananlysi work, including the post-irradiation examination of NUE spent fuel, has been completed successfully.The regulator has agreed to use NUE fuel in Qinshan CANDU-6 plants. The RU purchase has also been finished, and the RU powder which is coincident with the technical specification given by CE has been transported to China.

Now the critical path of this project is product-line modification ,and the main problem is how to treat radioactive liquid waste from the NUE fuel producing process. The China Institute of Atomic Energy (CIAE)was required to give solutions for this problem. The CIAE's scheme has been reviewed by experts in last year, but it is not perfect because of high cost and a great deal of solid waste. Now we are trying to improve CIAE's scheme to meet the requirement of NUE fuel production.

It is possible to start fuel product-line modification this year. The NUE full core implementation will begin once the modification is completed and the NUE fuel bundles are produced. All these work is hoped to be finished before the end of next year.

4.3. Advanced fuel CANDU reactor

To use recovered uranium more economically and with higher efficiency and steadily push ahead the use of thorium resource in PHWR, TQNPC has developed advanced fuel CANDU reactor (AFCR) in cooperation with domestic and overseas research entities. It is based on the enhanced CANDU6 reactor developed in Canada, fully incorporates the experience of Fukushima, and has achieved higher safety performance, to meet the technological requirements of G3 nuclear power units; it can also use and recycle uranium fuel and thorium fuel; therefore good economic performance can be expected. In terms of engineering maturity, the enhanced CANDU6 reactor has passed the safety review of three phases by Canadian Nuclear Safety Commission, and conditions are ready to carry out further work in conjunction with site.

In Nov. 2014, China Nuclear Energy Association(CNEA) organized experts of the industry to review the technical plan of advanced fuel CANDU reactor, it was concluded in the review that the advanced fuel CANDU reactor is feasible technologically with good safety performance, while retaining the production capacity of tritium and cobalt, it also has good fuel flexibility, therefore it is in line with the overall nuclear energy development strategy of China, with good prospects of development.

5. Conclusions

As China has made clear the technical strategy of nuclear closed fuel-cycle and has rich thorium resource, and CANDU is the best way to use RU and Th, CANDU could play an important role in Chinese nuclear power development. It could help to fully use the limited narural uranium resources, increase the economic performance of reprocessing, and develop the thorium nuclear utilization andthorium-uranium fuel cycle technology which can serve as supplement to the uranium-plutonium fuel cycle.Generally CANDU could be very conducive to ensuring the sustainable and healthy development of nuclear energy in China.

For years, Chinese and Canadian cooperators have made great efforts to develop CANDU advanced fuel technology following the CANDU advanced fuel technology development roadmap. The NUE implementation test has been competed successfully, which shows that NUE is suitable for current CANDU-6 plants. The NUE full core implementation is ongoing now and could be realized in near term. The AFCR with DRU fuel has been developed and have been reviewed and accepted by the experts panel organized by CNEA. The CANDU advanced fuel technology and AFCR will be developed continuously by Canadian and Chinese cooperators to meet the requirements of Chinese nuclear power development.

6. References

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